Are There Sensible Models of Dark Energy?

CPB @ McMaster University PI PERIMETER INSTITUTE

Astroparticle Symposium

Institute Pascal, Oct 30, 2023

Oui!

Non!

Non!

IS HINCHLIFFE'S RULE TRUE?*

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

*Accepted for publication in *Annals of Gnosis*.

ça dépend!

Wilson vs Occam

Theories

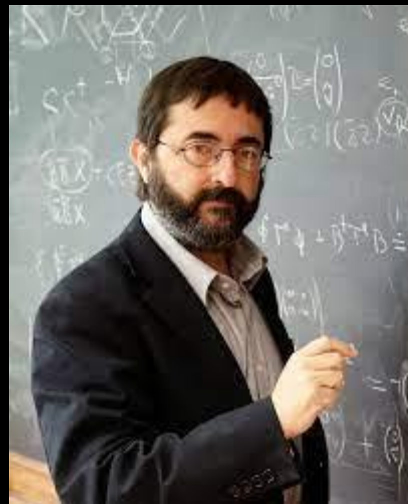
DE is hard to embed into a full theory of all of physics

Models

A cosmological constant is a great description of DE

ça dépend!

D. Dineen



F. Quevedo

P. Brax

Yoga models
2111.07286

dS & inflation
2202.05344

Axiodilaton tests
2212.14870

Screening
2310.02092

Based on earlier work on ubiquity of accidental symmetries in EFTs for string vacua
2006.06694

M. Ciupke

S. Krippendorf M. Cicoli

Outline

What do we know?

eq of state and time-dependence

What do we expect?

EFTs & domain of semiclassical methods

Scales and the low-energy limit

A case for light scalars?

Power-counting (against Horndeski)

A way forward?

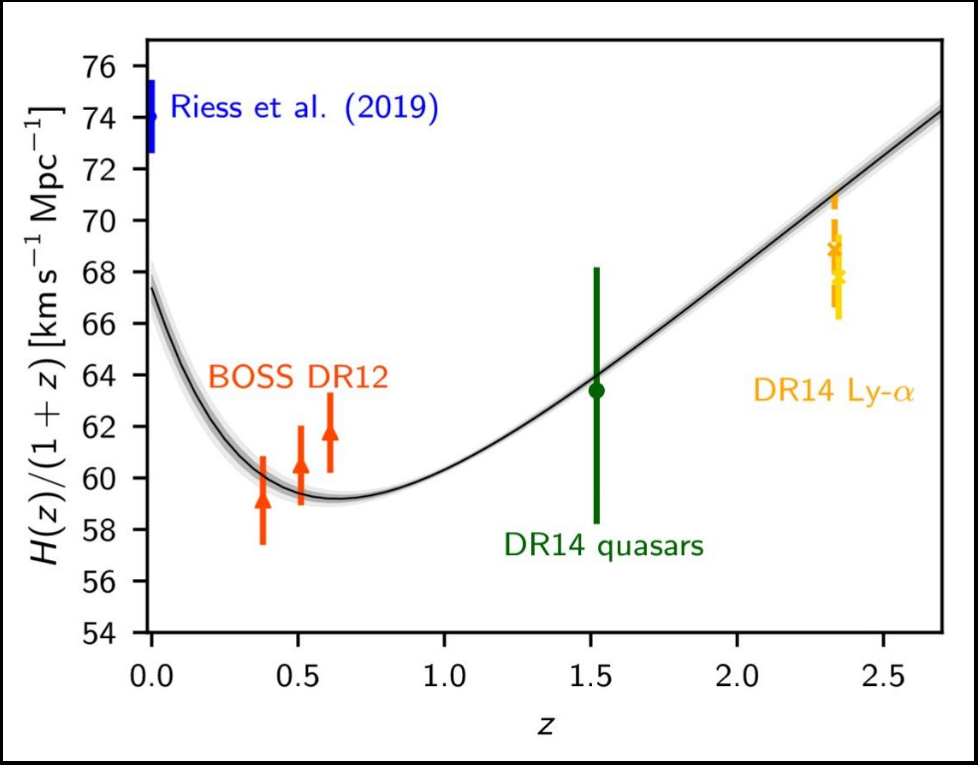
What do we know?

eq of state and time dependence

Properties of Dark Energy

Total abundance

Accelerated expansion is well-described by a cosmological constant Λ



Planck 2018

Table 2. Parameter 68% intervals for the base-ΛCDM model from *Planck* CMB power spectra, in combination with CMB lensing reconstruction and BAO.

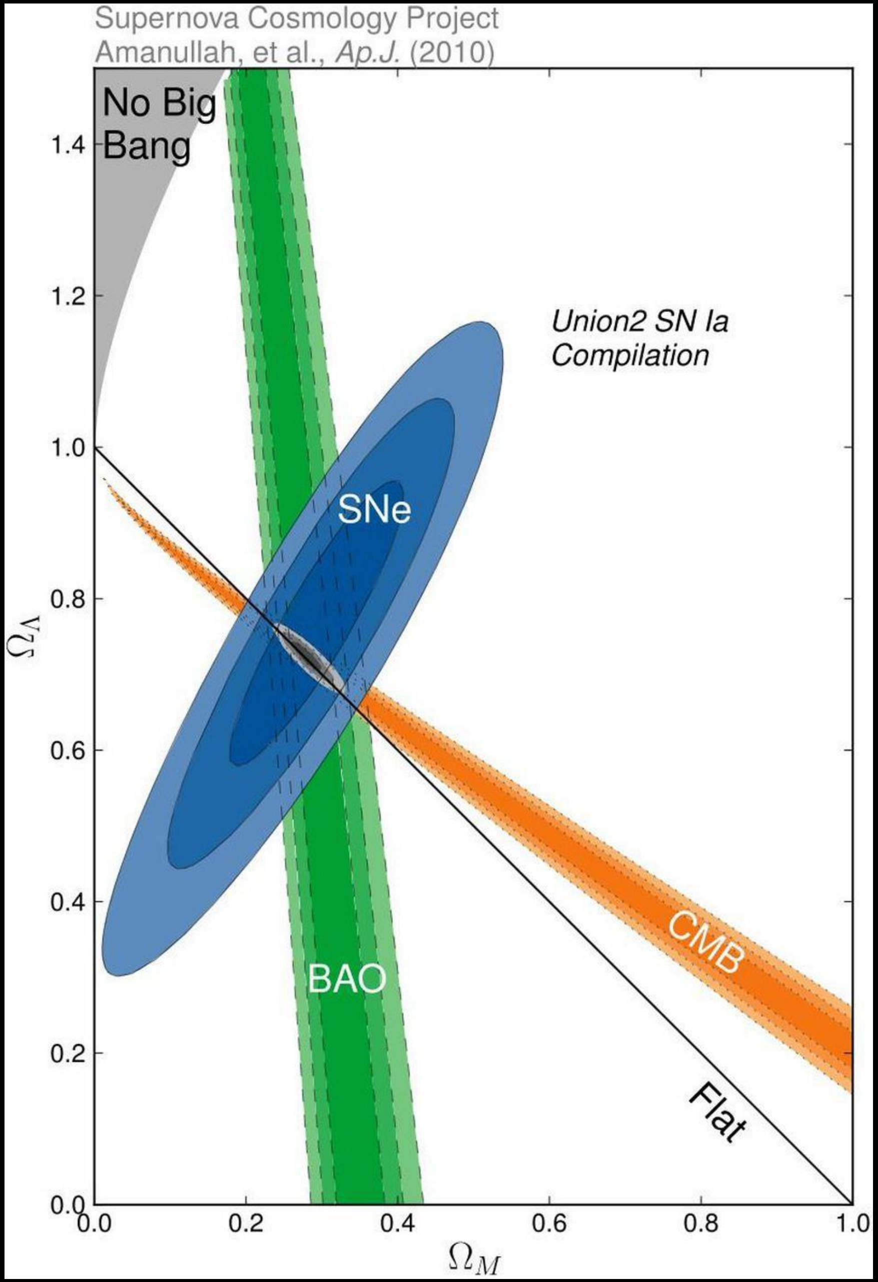
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
$H_0\ [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
$k_D\ [\mathrm{Mpc^{-1}}]$	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
$k_{eq}\ [\mathrm{Mpc^{-1}}]$	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020
f_{2000}^{143}	31.2 ± 3.0			29.5 ± 2.7	29.6 ± 2.8	29.4 ± 2.7
$f_{2000}^{143\times217}$	33.6 ± 2.0			32.2 ± 1.9	32.3 ± 1.9	32.1 ± 1.9
f_{2000}^{217}	108.2 ± 1.9			107.0 ± 1.8	107.1 ± 1.8	106.9 ± 1.8

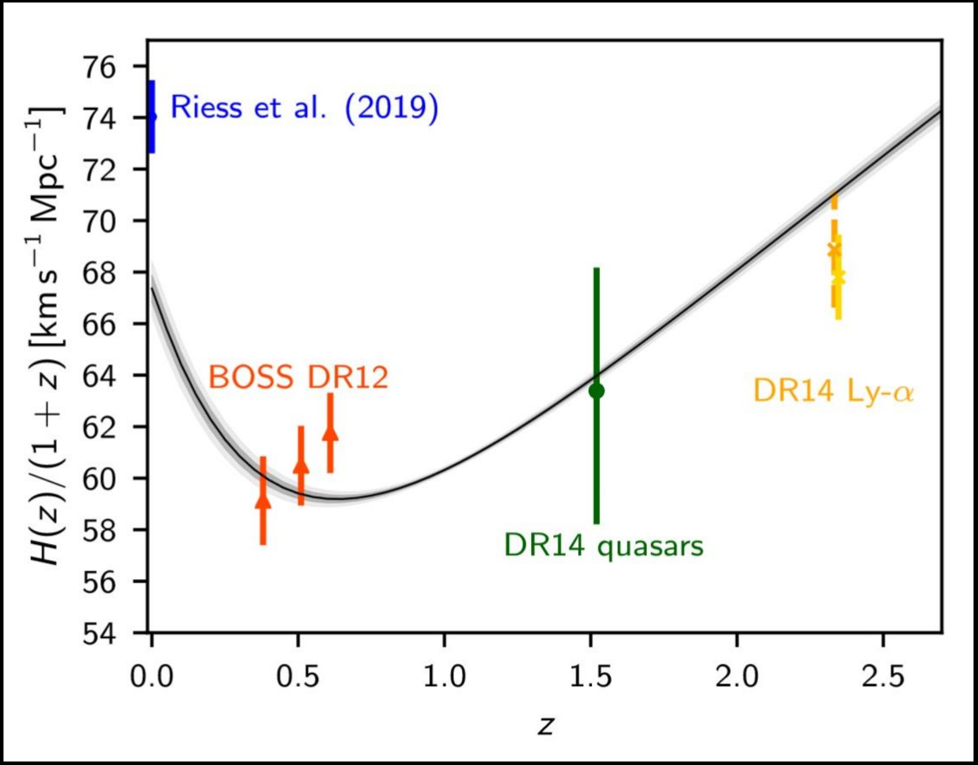
$$\rho_\Lambda \simeq 10^{-29}\mathrm{g/cm}^3 \simeq (3 \times 10^{-3}\mathrm{eV})^4$$

Planck 2018

Properties of Dark Energy

Total abundance

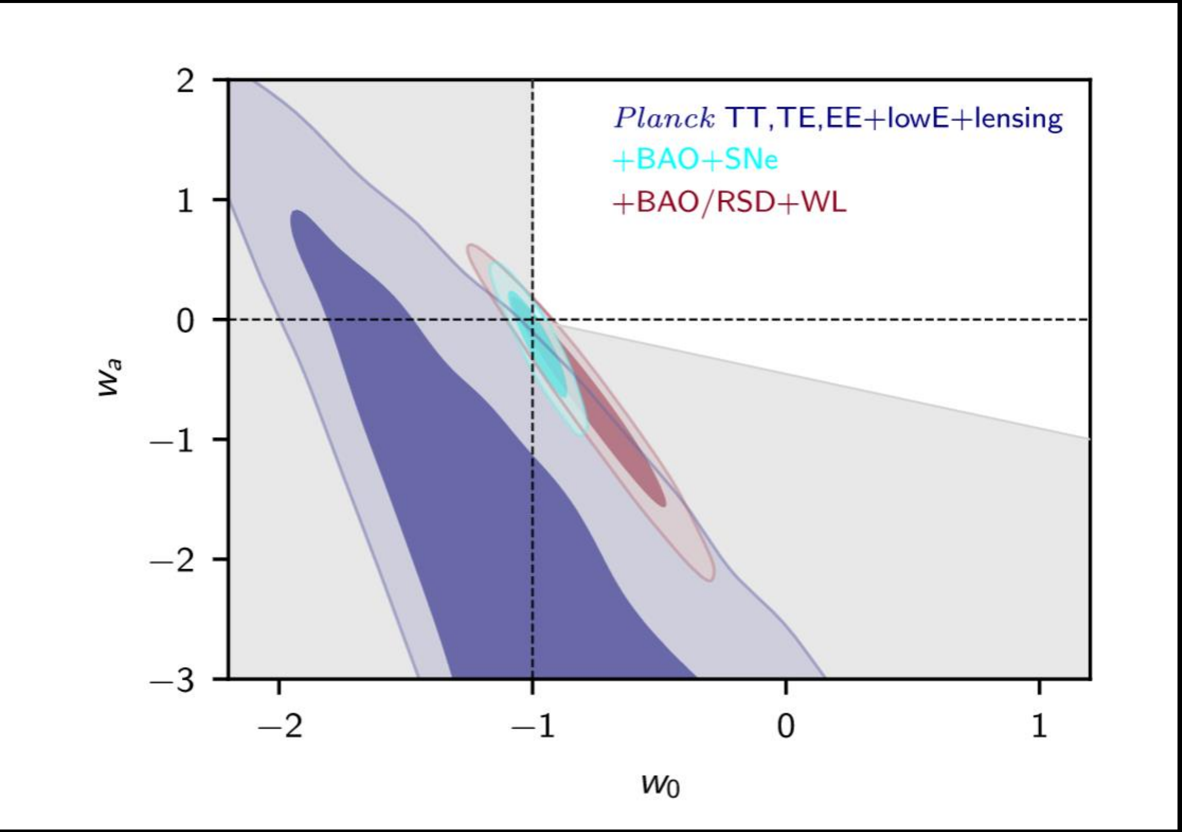




Planck 2018

Properties of Dark Energy

Planck 2018



$$w(a) = w_0 + (1 - a)w_a$$

Equation of state

$$p = w\rho$$

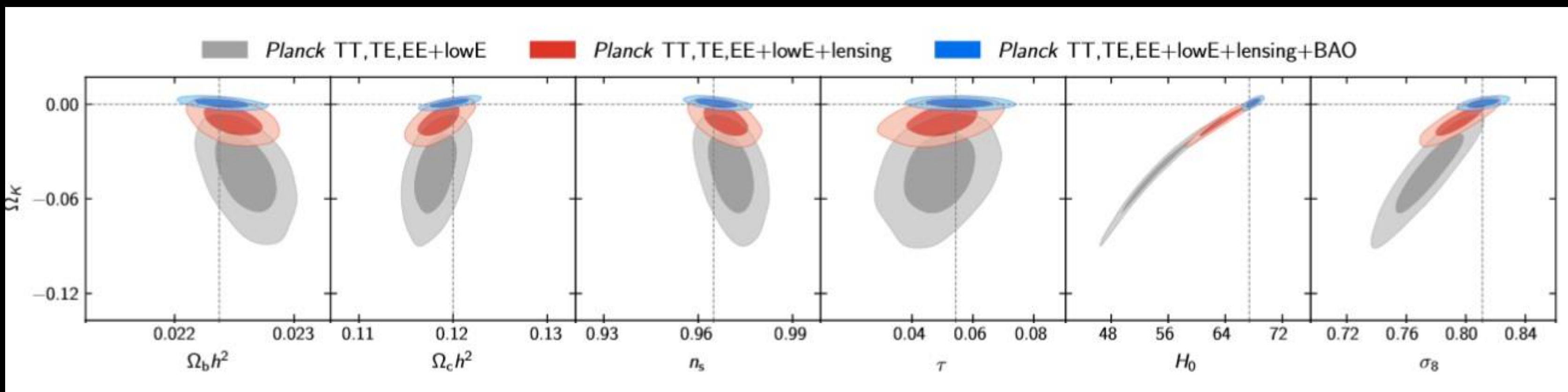
$$\rho \propto a^{-3(1+w)}$$

Such models are nonetheless explored because they can be tested by observations

Time-dependence of DE density is not required by the data

Models vs Theories

Planck 2018



Parameter	TT+lowE	TT, TE, EE+lowE	TT, TE, EE+lowE+lensing	TT, TE, EE+lowE+lensing+BAO
Ω_K	$-0.056^{+0.044}_{-0.050}$	$-0.044^{+0.033}_{-0.034}$	$-0.011^{+0.013}_{-0.012}$	$0.0007^{+0.0037}_{-0.0037}$
Σm_ν [eV]	< 0.537	< 0.257	< 0.241	< 0.120
$N_{\rm eff}$	$3.00^{+0.57}_{-0.53}$	$2.92^{+0.36}_{-0.37}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
Y_P	$0.246^{+0.039}_{-0.041}$	$0.240^{+0.024}_{-0.025}$	$0.239^{+0.024}_{-0.025}$	$0.242^{+0.023}_{-0.024}$
$dn_s/d\ln k$	$-0.004^{+0.015}_{-0.015}$	$-0.006^{+0.013}_{-0.013}$	$-0.005^{+0.013}_{-0.013}$	$-0.004^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.102	< 0.107	< 0.101	< 0.106
w_0	$-1.56^{+0.60}_{-0.48}$	$-1.58^{+0.52}_{-0.41}$	$-1.57^{+0.50}_{-0.40}$	$-1.04^{+0.10}_{-0.10}$

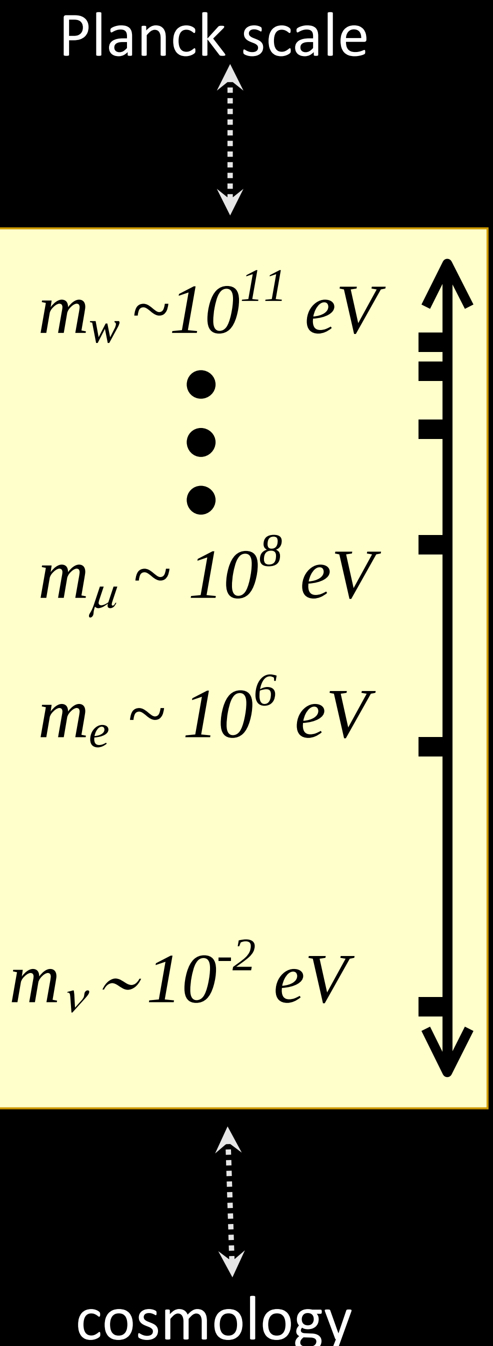
Curvature of space

Yet ALL viable theories of gravity have a curvature parameter *k*

Addition of spatial curvature also not required by the data

What do we expect?

Scales, EFTs & validity of semiclassical methods

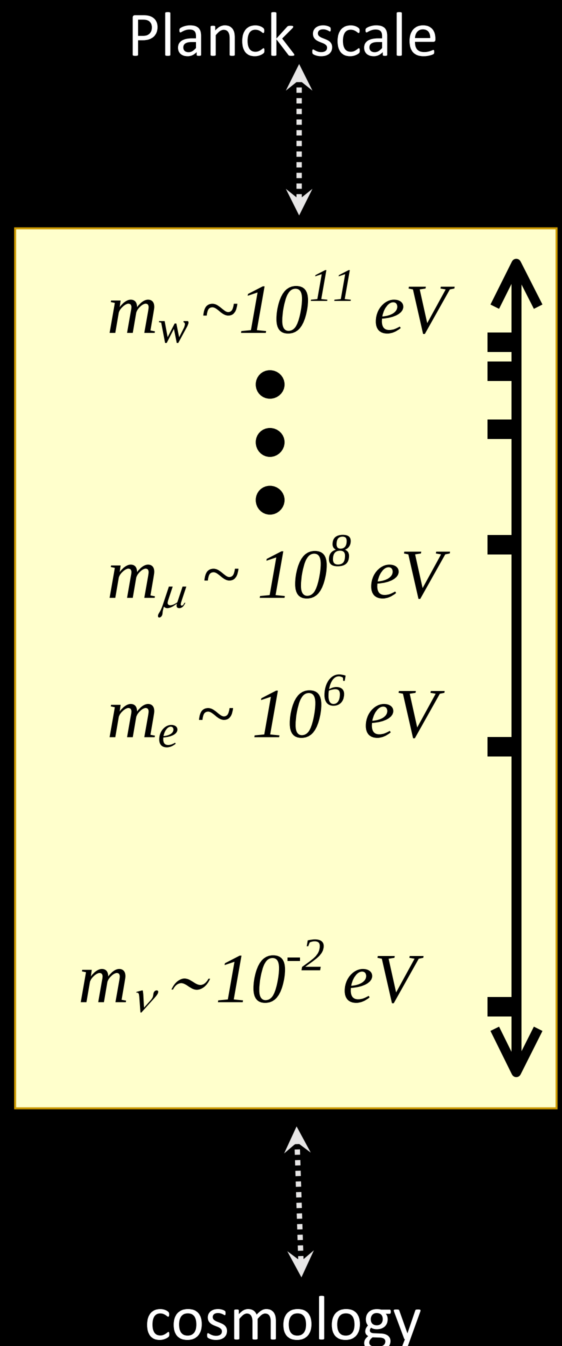


Life at Low Energies

Nature comes to us with many scales and effects of higher energy physics can be captured at low energies using a Wilsonian EFT

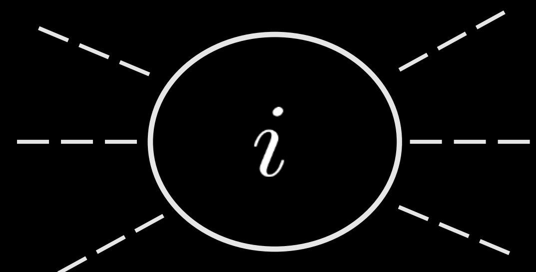
What does this say about what is expected on cosmological scales (the lowest energies to which we have access)?*

*(*NOT the Swampland program)*



Life at Low Energies

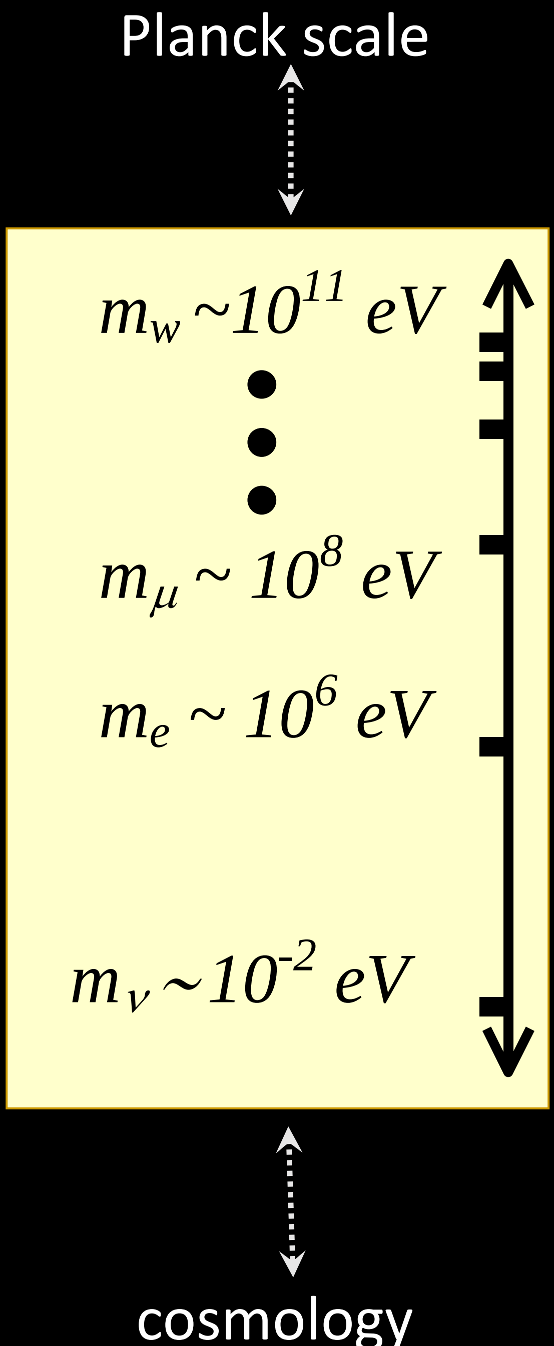
Integrating out particles of mass $m_i^2 >> R$:



$$\delta\mathcal{L}_W = \sqrt{-g}\Big(c_0 + c_1 R + c_2 R^2 + c_3 R^3 + \cdots\Big)$$

$$c_0 = \frac{1}{(4\pi)^2}\sum_i (-)^{F_i} a_i m_i^4$$

$$c_3 = \frac{1}{(4\pi)^2}\sum_i (-)^{F_i} \frac{b_i}{m_i^2}$$



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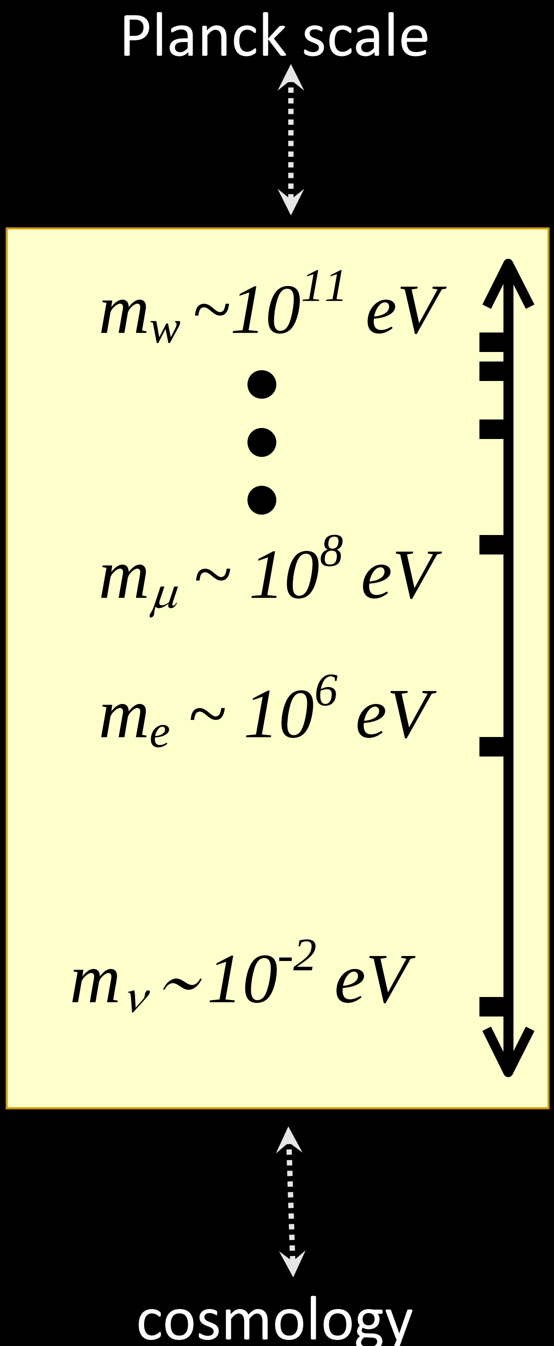
Smallest mass wins (in D dims) for interactions with dimension greater than D (*not Planck size)*



Life at Low Energies

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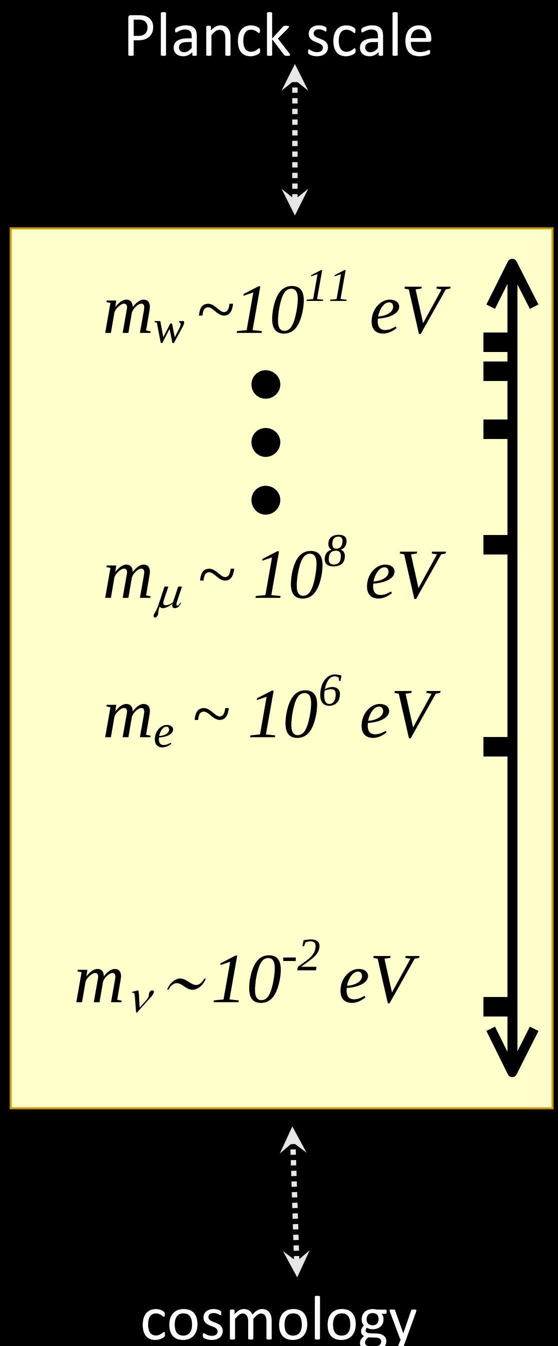
Smallest mass wins (in D dims) for interactions with dimension greater than D (*not Planck size)*

Largest mass wins (in D dims) for interactions with dimension less than D (usually *KK scale in 4D or string scale in higher D*)

Life at Low Energies



$$\delta\mathcal{L}_W = \sqrt{-g}\Big(c_0 + c_1 R + c_2 R^2 + c_3 R^3 + \cdots\Big)$$

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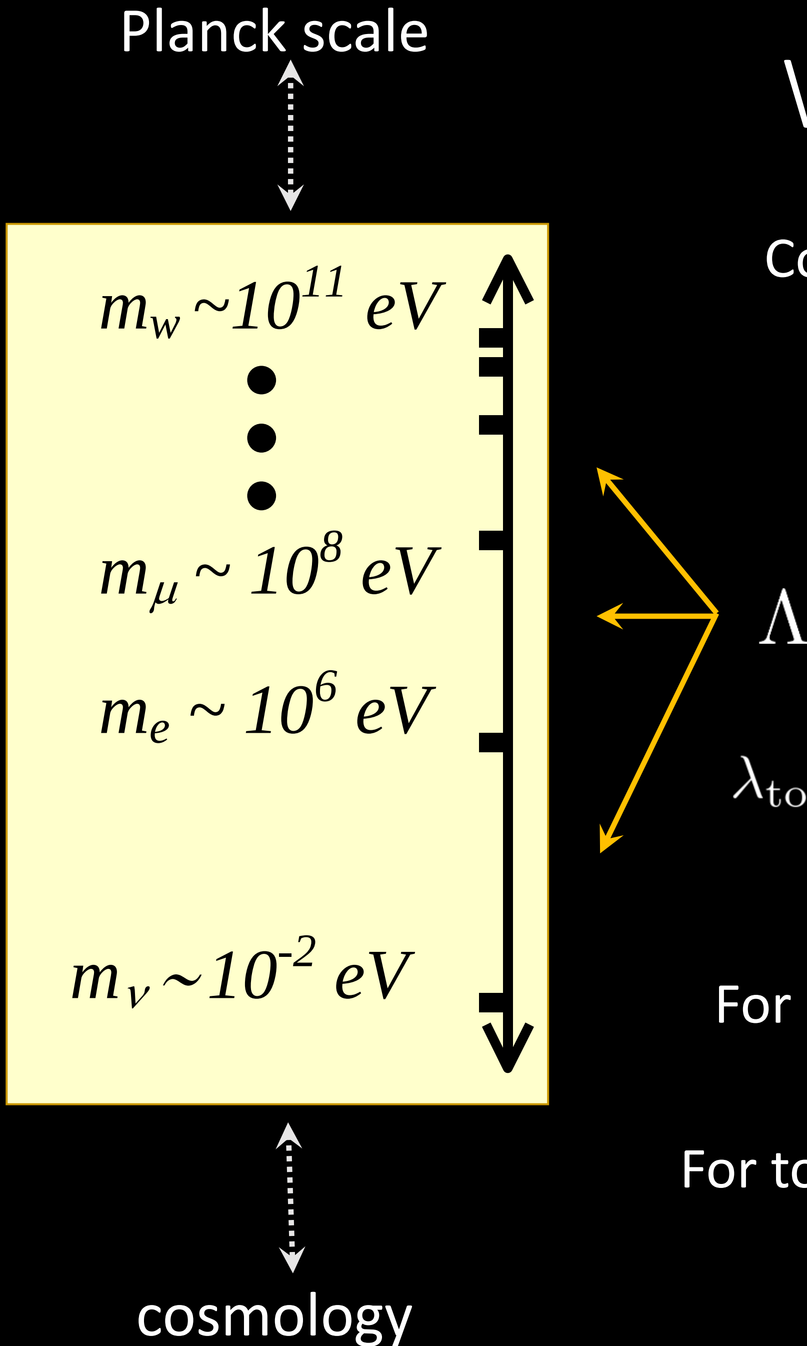
$$c_3 = \frac{1}{(4\pi)^2}\sum_i (-)^{F_i} \frac{b_i}{m_i^2}$$

Crucial exception: when symmetries forbid otherwise big contributions

(eg $c_0 = 0$ for unbroken supersymmetry because $a_B = a_F$ and $m_B = m_F$ so bosons cancel fermions)

What’s the Problem?



Cosmologists measure curvature, which is relatively simply related to c_0

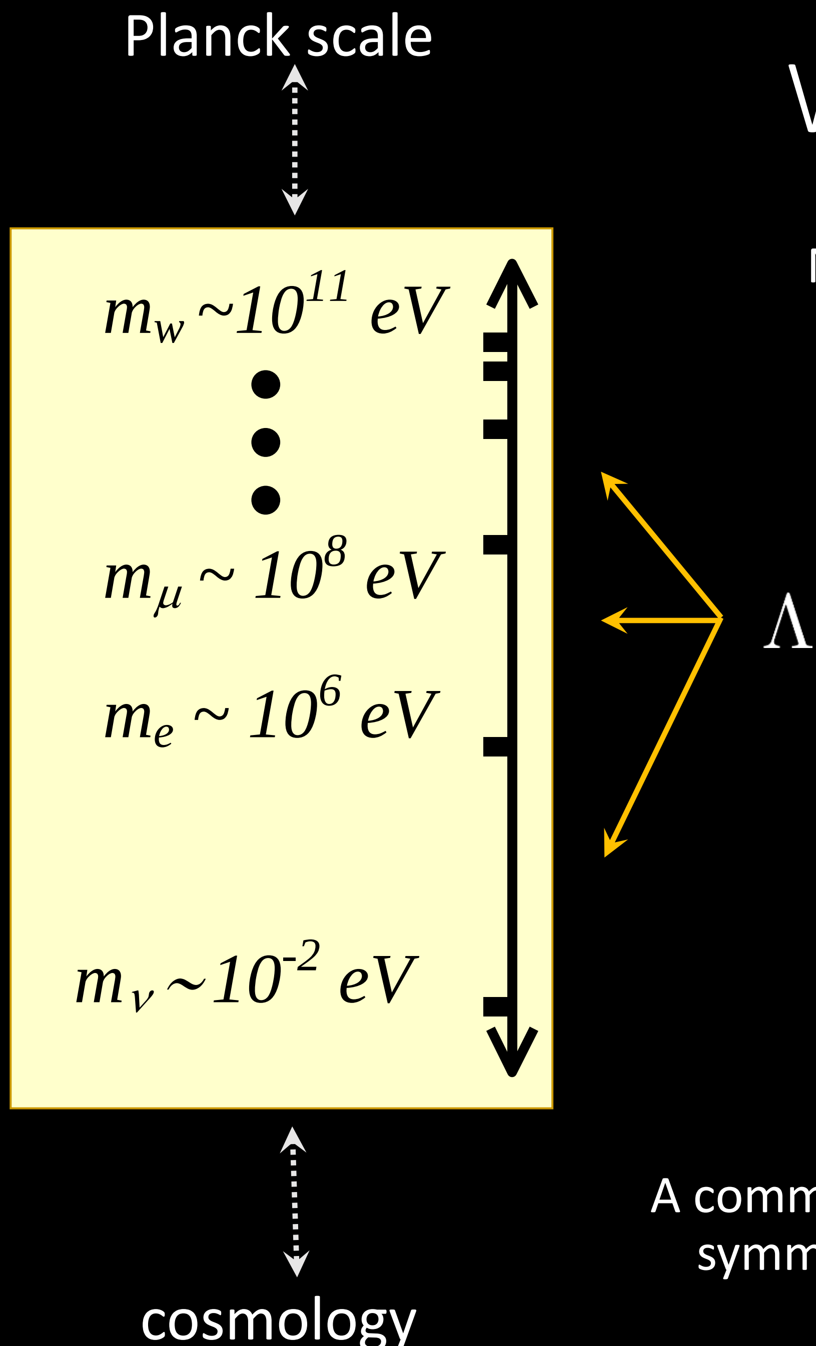
$$R_{\mu\nu} = \frac{\lambda_{\text{tot}}}{M_p^2} g_{\mu\nu}$$

$$\lambda_{\text{tot}} = \lambda_0(\Lambda) + \frac{1}{(4\pi)^2} \sum_{m_i < \Lambda} (-)^{F_i} a_i m_i^4$$

For electron this requires cancelation of 32 decimal places between λ_0 and loop

For top quark this requires cancelation of 54 decimal places between λ_0 and loop

What's the Problem?



Nature has many hierarchies (not just in particle physics) and this is not what happens for *any* of the others

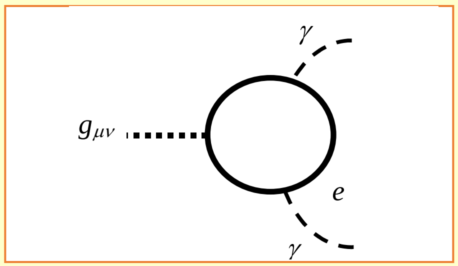
Other known hierarchies are all '*technically natural*':

> If a measured coupling g_{tot} is small then g is small for *any EFT* in which one cares to ask the question

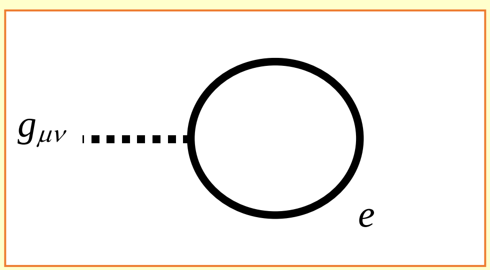
A common sufficient condition: if there is more symmetry in the limit $g = 0$ ('*t Hooft natural*')

What's the Problem?

Why this?



But not this?



$$R_{\mu\nu} = \frac{\lambda_{\text{tot}}}{M_p^2}\, g_{\mu\nu}$$

Seek a reason why quantum contributions to vacuum energies are *either* small *or* do not gravitate.

BUT *success of equivalence principle also requires quantum energies to gravitate in atoms and nuclei.*

Cannot solve this at high energies because even the *electron* has a problem

The Dark Energy Opportunity

The success of cosmology *requires* Nature to have a feature that is NOT generic at low energies

There are many models of time-dependent Dark Energy and cosmological observations alone cannot distinguish amongst most of them.

Yet embedding them into the rest of physics is difficult enough that it has not been convincingly done.

This is likely a crucial clue: If an example can be found it is likely how Nature works.

A Light-Scalar Surprise

Sigma models vs Horndeski

A Light-Scalar Surprise

Particle physicists usually argue that light scalar fields are also NOT generic at low energies

A technically natural Dark Energy density makes them *more* likely rather than less likely

BUT we are likely looking for them in the wrong way (by doing so using eg Horndeski models).

Light Gravitating Scalars

What should the low-energy dynamics of gravitating scalars look like?

$$\mathcal{L}_W = -\sqrt{-g}\Big[v^4 U(\phi) + \tfrac{1}{2}M_p^2 R + \tfrac{1}{2}f^2 \mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b + c_2 R^2 + \cdots\Big]$$

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It is technically natural for *f* to be large, so choose *f* = M_p for simplicity

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$$M_p^2\,R_{\mu\nu} + M_p^2\,\mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial_\nu\phi^b + v^4 U(\phi) g_{\mu\nu} + \cdots = 0$$

$$M_p^2\Big[\nabla^\mu\nabla_\mu\phi^a + \Gamma^a_{bc}\partial_\mu\phi^b\partial^\mu\phi^c\Big] - v^4\mathcal{G}^{ab}\partial_b U + \cdots = 0$$

It is technically natural for *v* to be large, but we must keep $v^2 = H M_p$ with $H \ll M_p$ if the derivative expansion is to be valid (*the cc problem*)

Light Gravitating Scalars

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$$\mathcal{L}_W = -\sqrt{-g}\left[v^4 U(\phi) + \tfrac{1}{2}M_p^2 R + \tfrac{1}{2}M_p^2\,\mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b + c_2 R^2 + \cdots\right]$$

If *v* is small and if *U* and G_{ab} are order unity then the scalar mass is generically:

$$\mu \sim \frac{v^2}{f} \sim \frac{v^2}{M_p}$$

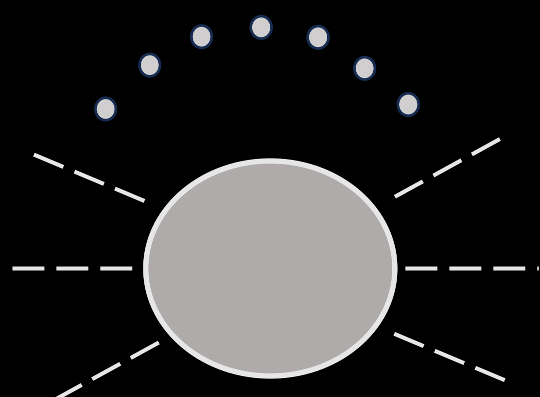
In a world where it is understood why the cc problem is solved any gravitationally coupled scalar has a Hubble-scale mass!

astro-ph/0107573

Light Gravitating Scalars

Will now argue why the derivative expansion is *compulsory* if one works semiclassically (as everyone does)

$$\mathcal{L}_W = -\sqrt{-g}\Big[v^4 U(\phi) + \tfrac{1}{2}M_p^2 R + \tfrac{1}{2}M_p^2\,\mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b + c_2 R^2 + \frac{c_3}{m^2}R^3 + \cdots\Big]$$



Evaluate a correlation function with *E* external lines, *L* loops and V_n vertices involving d_n derivatives with curvature *H* and external momenta *k/a=H*

Light Gravitating Scalars

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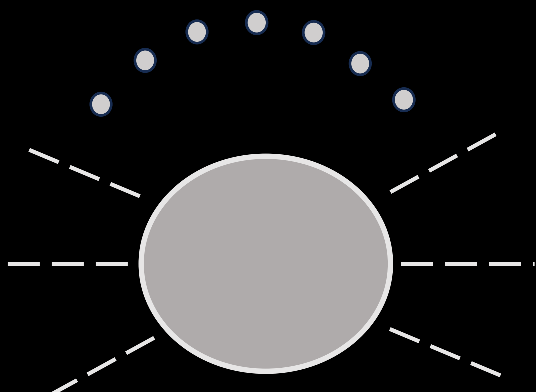
$$\mathcal{L}_W = -\sqrt{-g}\Big[v^4 U(\phi) + \tfrac{1}{2}M_p^2 R + \tfrac{1}{2}M_p^2\,\mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b + c_2 R^2 + \frac{c_3}{m^2}R^3 + \cdots\Big]$$



Evaluate a correlation function with *E* external lines, *L* loops and V_n vertices involving d_n derivatives with curvature *H* and external momenta *k/a=H*

0902.4465

1708.07443

$$\mathcal{B}_E(H) \simeq M_p\left(\frac{H^2}{M_p}\right)^{E-1}\left(\frac{H}{4\pi\,M_p}\right)^{2L} \times \prod_{d_n\geq 4}\left[\left(\frac{H}{M_p}\right)^2\left(\frac{H}{m}\right)^{d_n-4}\right]^{V_n}\prod_{d_n=0}\left(\frac{v^4}{H^2M_p^2}\right)^{V_n}$$

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}\right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

Each loop costs: $\left(\frac{H}{4\pi\, M_p}\right)^2$

The semiclassical approximation *relies* on the derivative expansion

Light Gravitating Scalars

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Each higher-derivative interaction costs an *additional*: $\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}$

4- and higher-derivative interactions are ***always*** suppressed at low energies when the semiclassical approximation is under control

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n-4}\right]^{V_n} \prod_{d_n=0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

Each zero-derivative interaction ***amplifies*** by an *additional*: $\dfrac{v^4}{H^2 M_p^2}$

This generically undermines the derivative expansion (and semiclassical control)

It need not be a problem ***if*** $v^2 = HM_p$ or smaller

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}\right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

There is *no penalty* for 2-derivative terms

This is why GR nonlinearities cannot be neglected at low energies

It also shows that 2-derivative scalar interactions scale the same as does GR (and are similar in size when $f = M_p$)

Light Gravitating Scalars

We should expect two-derivative scalar self-interactions to compete with GR for any scalars light enough to be relevant in cosmology

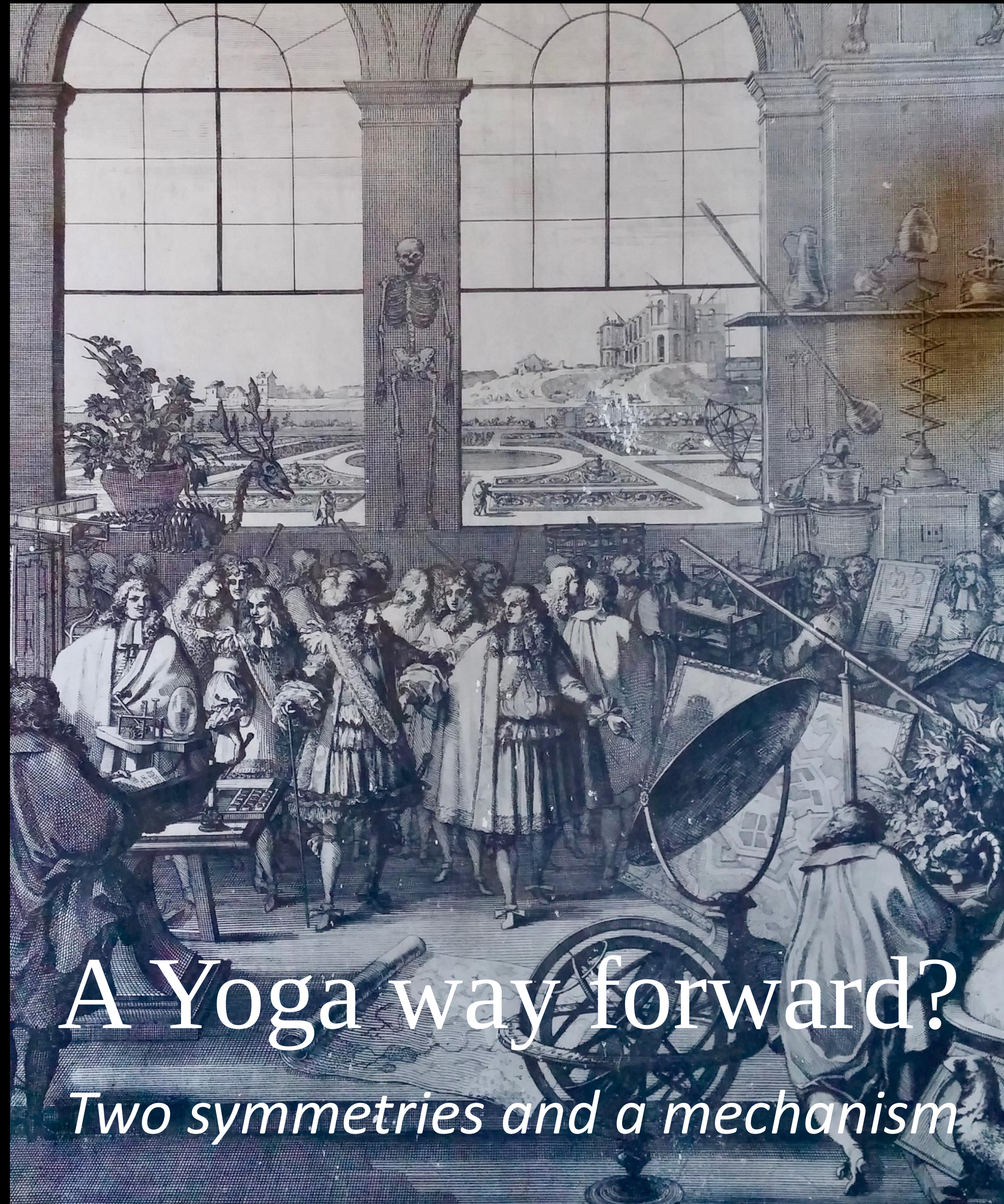
BAD NEWS

Almost all efforts at testing scalar-tensor theories for simplicity specialize to a single scalar

Two-derivative interactions can be removed using a field redefinition if the metric G_{ab} is flat

For all single-field models the metric G_{ab} is flat

This is why it is so difficult to get single-scalar (eg Horndeski models) to be competitive with gravity at low energies



A Yoga way forward?

Two symmetries and a mechanism

Is progress on the CC problem possible?

The missing step is to have a technically natural explanation for why the scale *v* of the scalar potential should be small.

Best scenario so far uses the interplay between supersymmetry (of the gravity sector) and accidental scale invariance, such as suggested by low-energy string vacua.

Yoga Models use these symmetries to build a 'natural relaxation' mechanism that does suppress the vacuum energy (and improve on extra-dimensional approaches to the cosmological constant problem).

These models also imply the existence of multiple light scalars, as seems generic to approaches to Technically Natural cc.

Scaling Symmetries

String vacua (and therefore also essentially all extra-dimensional supergravities) share a class of accidental approximate scaling symmetries

$$g_{\mu\nu} \to \lambda^r \, g_{\mu\nu} \qquad \Phi \to \lambda^s \, \Phi \qquad \mathscr{L} \to \lambda^p \, \mathscr{L}$$

Witten 85
CPB, Font & Quevedo 85
2006.06694

Scaling Symmetries

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WHY? String theory has no parameters so all perturbative expansions are in powers of fields

$$\mathscr{L} = \sum_{mn} f_{mn} \, \Phi^m \, \Psi^n$$

$$\Phi \to \lambda^p \Phi \qquad \Psi \to \lambda^q \Psi \qquad \mathscr{L}_{mn} \to \lambda^{mp+nq} \mathscr{L}_{mn}$$

Evidence for Accidental Scaling

11D sugra: $\mathscr{L}_{11} \to \lambda^9 \mathscr{L}_{11}$

$$g_{MN} \to \lambda^2 g_{MN}$$
$$A_{MNP} \to \lambda^3 A_{MNP}$$

+ fermion transfns

10D IIB sugra: $\mathscr{L}_B \to \lambda^{4u} \mathscr{L}_B$

$$g_{MN} \to \lambda^u g_{MN} \qquad B_{MN} \to \lambda^{2u-w} B_{MN}$$
$$C_{MN} \to \lambda^w C_{MN} \qquad \tau \to \lambda^{2(w-u)} \tau$$
$$C_{MNPR} \to \lambda^{2u} C_{MNPR}$$

+ fermion transfns

and so on for Type I and IIA and heterotic vacua corresponding to g_s and α' expansions..

Accidental Scaling can enforce V = 0 at extremum

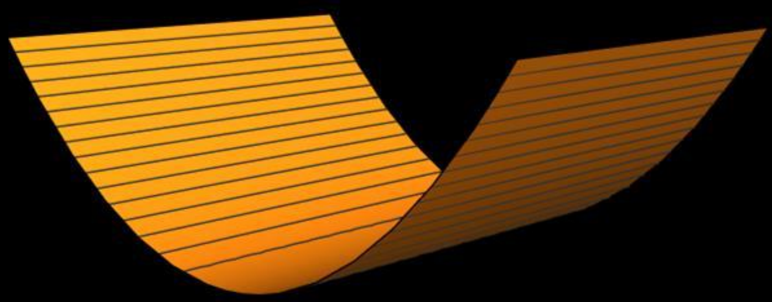
$$V(\lambda^p \phi) = \lambda^w V(\phi)$$

$$\sum_i p_i \phi^i \left(\frac{\partial V}{\partial \phi^i} \right) = w V(\phi)$$

if $\frac{\partial V}{\partial \phi^i} = 0$ then* $V = 0$

$$p_j \frac{\partial V}{\partial \phi^j} + \sum_i p_i \phi^i \frac{\partial^2 V}{\partial \phi^i \partial \phi^j} = w \frac{\partial V}{\partial \phi^j}$$

if $\phi^i = 0$ then* $\frac{\partial V}{\partial \phi^i} = 0$



V = 0 despite scaling symmetry being spontaneously broken!

Corrections to scaling

Not actually a symmetry

$$\mathscr{L} \rightarrow \lambda^w \mathscr{L}$$

Even if it were a classical symmetry, it is usually anomalous

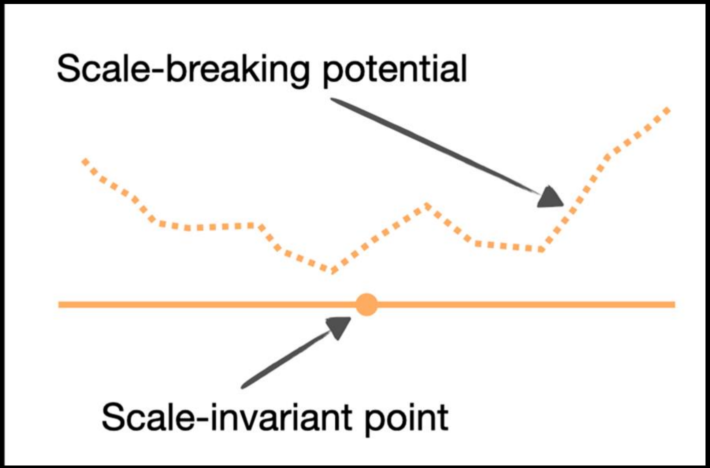
Peccei et al 87
Wetterich 88

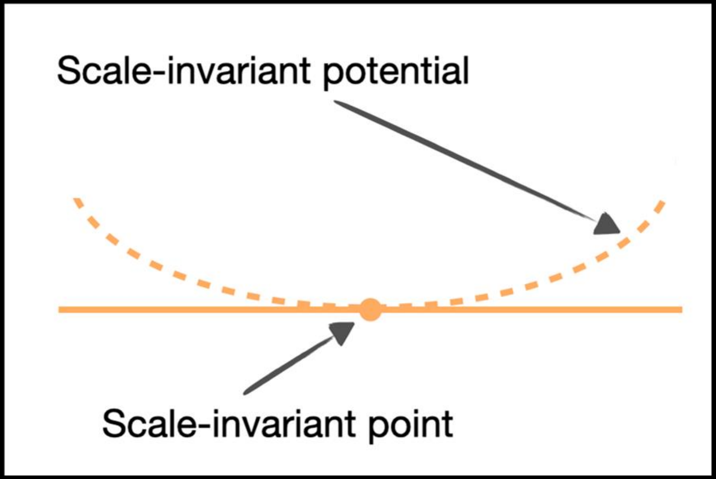
Weinberg No Go: Even if unbroken, scale inv cannot forbid lifting of flat direction

Weinberg 89

Restricting the lifting of flat directions is where supersymmetry might help

2006.06694





Scaling and 4D Supersymmetry

Can supersymmetry combine with scale invariance to suppress lifting of flat directions?

4D susy specified by functions *K(z,z*), W(z), f_{ab}(z)*

$$\mathcal{L}_g = \sqrt{-\tilde{g}}\, e^{-K/3} \widetilde{R}$$

$$\mathscr{L} = \int d^4\theta\, \overline{\Phi}\, \Phi\, e^{-K/3} + \int d^2\theta \left[\Phi^3 W + f_{ab} \overline{\mathscr{F}}^a \mathscr{F}^b \right] + \text{c.c.}$$

$$\mathscr{L}_{\text{kin}} = -\sqrt{-g}\, K_{i\bar{j}}\, \partial_\mu z^i\, \partial^\mu \bar{z}^j$$

$$V(z,\bar{z}) = e^K \left[K^{i\bar{j}}\, D_i W \overline{D_j W} - 3\,|W|^2 \right]$$

$$D_i W = W_i + K_i W$$

Scaling and 4D Supersymmetry

Can supersymmetry combine with scale invariance to suppress lifting of flat directions?

$$\mathscr{L} = \int d^4\theta \, \overline{\Phi} \, \Phi \, e^{-K/3} + \int d^2\theta \left[\Phi^3 W + f_{ab} \overline{\mathscr{F}}^a \mathscr{F}^b \right] + \text{c.c.}$$

4D susy specified by functions *K(z,z*), W(z),* $f_{ab}(z)$

$$\mathscr{L}_{\text{kin}} = -\sqrt{-g}\, K_{i\bar{j}}\, \partial_\mu z^i \, \partial^\mu \bar{z}^j$$

$$V(z, \bar{z}) = e^K \left[K^{i\bar{j}}\, D_i W \overline{D_j W} - 3\,|W|^2 \right]$$

$$D_i W = W_i + K_i W$$

Scale invariance implies rules for how *W*, f_{ab} and $e^{-K/3}$ scale as the fields *z* scale

Scaling and 4D Supersymmetry

No-Scale supergravity: scalar potential has a flat direction along which susy breaks

Cremmer et al 83
Barbieri et al 85

if $z^i \to \lambda z^i$ implies $e^{-K/3} \to \lambda e^{-K/3}$

then $K^{i\bar{j}} K_i K_{\bar{j}} = 3$

'no-scale' model

Special things happen if $e^{-K/3}$ is homogeneous degree 1:

Sufficient condition for no-scale model, so provides flat directions along which susy is broken

0811.1503

if $W_i = 0$ then

$$V = e^K \left[K^{i\bar{j}} K_i K_{\bar{j}} - 3 \right] |W|^2 = 0$$

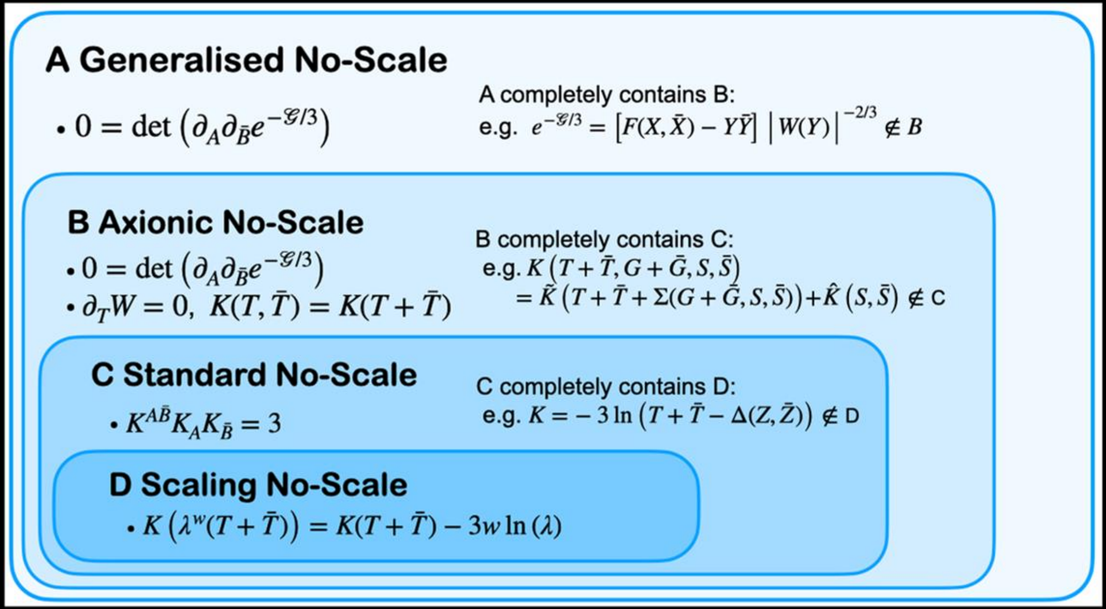
$$D_i W = W_i + K_i W = K_i W \neq 0$$

Scaling and 4D Supersymmetry

Scale invariance is ***sufficient*** for no-scale supergravity, but is ***not necessary***.

$$e^{-K/3} = T + T^* + f(z, z^*)$$

No-scale condition is sufficient for flat directions, but is also not necessary



2006.06694

A mechanism

Flat directions can persist in no-scale models to higher orders than naively expected

e.g. suppose Φ^{-1} is an expansion field and scale invariance gives leading scale invariant result

scale invariant & no-scale

$$e^{-K/3} = A_0 \, \Phi$$

Flat directions can persist at subleading order 'by accident'

Not scale invariant

but still no-scale

$$e^{-K/3} = A_0 \, \Phi + A_1$$

though are eventually lifted

neither

$$e^{-K/3} = A_0 \, \Phi + A_1 + \frac{A_2}{\Phi}$$

Extended No-Scale Structure

This actually happens in some string compactifications

Berg, Haack & Kors 05
Berg, Haack & Pajer 07
Cicoli, Conlon & Quevedo 08

$$e^{-K/3} = (\tau - \tau^*)^{1/3} A_0 \mathcal{V}^{2/3} \left[1 + \frac{B_n}{\mathcal{V}^{2/3}} (\tau - \tau^*)^{1-n} + \cdots \right]$$

corresponding to an α'^2 string loop correction

These corrections preserve the flat direction for V to order α'^3 when evaluated at $D_\tau W = 0$

Supergravity Coupled to nonSUSY matter

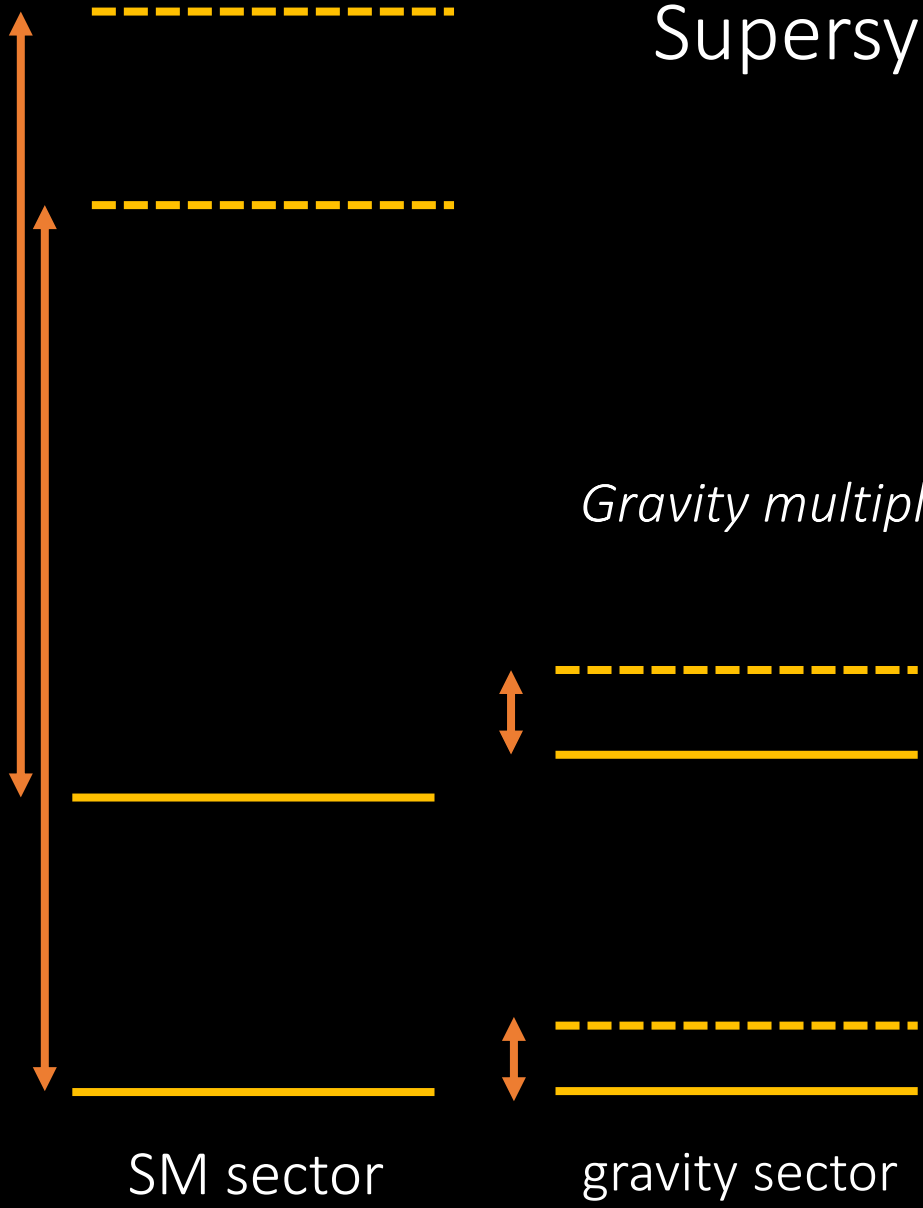
How to couple this to SM fields?

How can supersymmetry play a role at low energies when we know the Standard Model is not supersymmetric?

Supersymmetric Gravity Sector

$$\Delta m^2 = m_B^2 - m_F^2 \sim gF$$

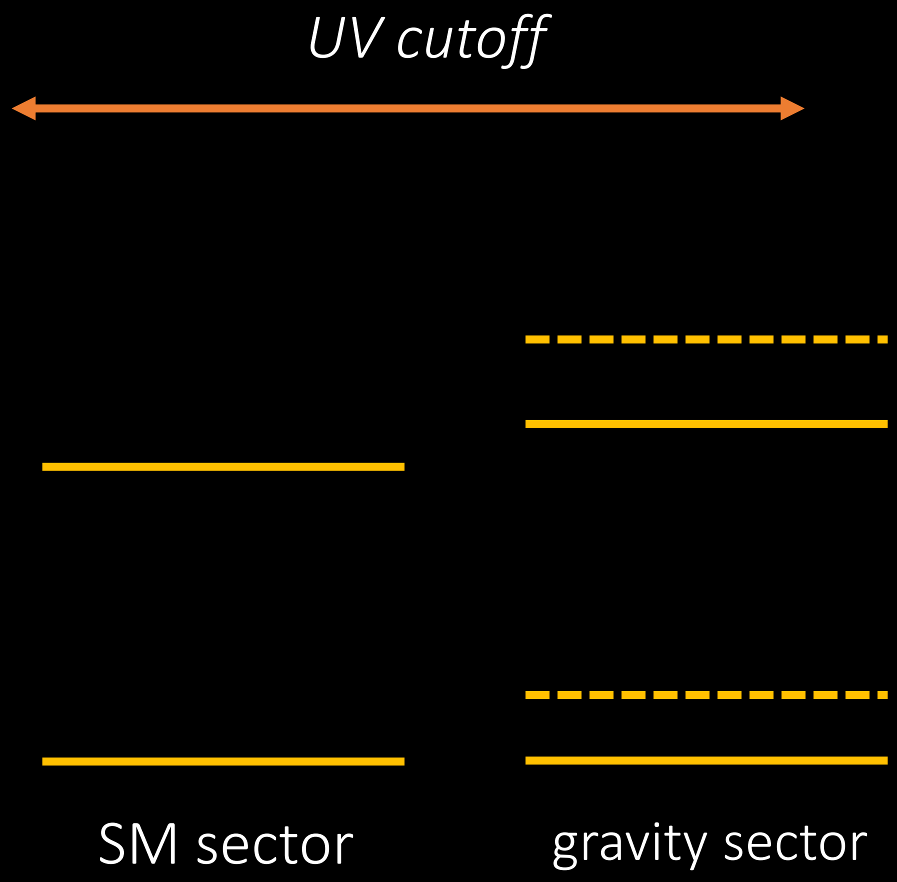
Gravity multiplet typically split by less than others because gravity is a weak force



Supersymmetric Gravity Sector

General coupling of supergravity to nonsupersymmetric matter is known

Komargodsky & Seiberg 09
Bergshoeff et al 15
Dallagata & Farakos 15
Schillo et al 15
Antoniadis et al 21
Dudas et al 21



Supersymmetric Gravity Sector

Why should it matter if gravity is supersymmetric when the SM sector is not supersymmetric anyway?

Auxiliary fields are important in the low-energy scalar potential (and so also for naturalness arguments)

Non-propagating – topological – fields play similarly important roles in eg Quantum Hall systems.

Auxiliary fields similarly start life as topological fields in higher dimensions

Bielleman, Ibanez & Valenzuela 15
1509.04209

Yoga Models

Coupling to SM fields

There is a dilaton supermultiplet: $T = \{\tau + i\, a\,,\ \xi\}$

Action arises as expansion in dilaton field $\tau = T + T^*$

Goldstino *X* and other fields *Y* enter in nonsupersymmetric way

$$\mathcal{P} := e^{-K/3} = \tau - k + \frac{h}{\tau} + \cdots$$

$$k = k_0(Y, \overline{Y}) + \boxed{[k_X(Y, \overline{Y})X + \text{h.c.}] + \overline{X}X \text{ term}}$$

$$W = w_0(Y) + \boxed{w_X(Y, \overline{Y})X}$$

NEW

2111.07286

Yoga Models

Coupling to SM fields

There is a dilaton supermultiplet: $T = \{\tau + i\, a\, ,\ \xi\}$

Action arises as expansion in dilaton field $\tau = T + T^*$

Goldstino X and other fields Y enter in nonsupersymmetric way

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$$k = k_0(Y, \overline{Y}) + [k_X(Y, \overline{Y})X + \text{h.c.}] + \overline{X}X \text{ term}$$

$$W = w_0(Y) + w_X(Y, \overline{Y})X$$

$$F^X = e^{K/2} K^{X\overline{B}} (w_{\overline{B}} + K_{\overline{B}} w_0)$$

Must keep this large to use nonlinearly realized susy

Yoga Models

Coupling to SM fields

There is a dilaton supermultiplet: $T = \{\tau + i\, a\,,\ \xi\}$

Action arises as expansion in dilaton field $\tau = T + T^*$

Goldstino X and other fields Y enter in nonsupersymmetric way

$$\mathcal{P} := e^{-K/3} = \tau - k + \frac{h}{\tau} + \cdots$$

$$k = k_0(Y, \overline{Y}) + [k_X(Y, \overline{Y})X + \cdots] + \cdots$$

As opposed to just this

$$W = w_0(Y) + w_X(Y, \overline{Y})X$$

$$F^X = e^{K/2} K^{X\overline{B}}(w_{\overline{B}} + K_{\overline{B}} w_0)$$

Must keep this large to use nonlinearly realized susy

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

Leading part of the matter/dark interactions has the form:

axio-dilaton: T = τ + i a

$$\tilde{g}_{\mu\nu} \simeq \frac{g_{\mu\nu}}{\tau}$$

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad\qquad m_\nu \propto \frac{M_p}{\tau}$$

This actually works numerically if $\tau_{\rm min} \sim 10^{28}$

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

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$$V(\tau) \simeq M_p^4 \left[\frac{w_X^2}{\tau^2} + \frac{A w_X}{\tau^3} + \frac{B}{\tau^4} + \cdots\right]$$

w_X, A, B functions of other fields and $\ln \tau$

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

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$\mathcal{O}(m_{sm}^4)$

NOT SMALL

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

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$$V(\tau) \simeq M_p^4 \left[\frac{w_x^2}{\tau^2} + \frac{A w_X}{\tau^3} + \frac{B}{\tau^4} + \cdots \right]$$

Introduce 'relaxation' field that seeks minimum of w_x terms

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln\tau)$$

$$V(\tau) \simeq M_p^4 \left[\frac{w_X^2}{\tau^2} + \frac{A w_X}{\tau^3} + \frac{B}{\tau^4} + \cdots\right]$$

Introduce 'relaxation' field that seeks minimum of w_x terms

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$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad V(\tau) \simeq \frac{M_p^4}{\tau^4}\, U(\ln\tau)$$

$$\ln\tau_{\rm min} \sim 65 \qquad \tau_{\rm min} \sim 10^{28}$$

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad\qquad V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln\tau)$$

$$V_{\rm min} \propto \frac{M_p^4}{\tau_{\rm min}^4} \propto \left(\frac{m_{sm}^2}{M_p} \right)^4$$ 👀

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$F \sim \frac{w_0}{\tau^{3/2} M_p} \qquad w_0 \sim M_p^3\, \tau_{\rm min}^{1/2}$$

$$V_{\rm min} \sim \frac{\epsilon^5 |w_0|^2}{\tau_{\rm min}^4 M_p^2} \sim \frac{\epsilon^5}{\tau_{\rm min}}\; F^* F$$

$$\epsilon \sim 1/(\log \tau_{\rm min})$$

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

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$$V_{\rm min} \sim \frac{\epsilon^5 |w_0|^2}{\tau_{\rm min}^4 M_p^2} \sim \boxed{\frac{\epsilon^5}{\tau_{\rm min}}} F^* F$$

Out of the box: $V_{min} = 10^{-91}\, M_p^{\,4}$ (not *quite* 10^{-120}*, but…)*

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

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$$V_{\rm min} \sim \frac{\epsilon^5 |w_0|^2}{\tau_{\rm min}^4 M_p^2} \sim \boxed{\frac{\epsilon^5}{\tau_{\rm min}}} F^* F$$

Small V_{min} implies small τ mass: below $10^{-80}\, M_p^{\,4}$ must worry about long-range forces in the solar system (WIP)

Overview

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}\right] + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$F \sim \frac{w_0}{\tau^{3/2} M_p} \qquad w_0 \sim M_p^3\, \tau_{\rm min}^{1/2}$$

$$V_{\rm min} \sim \frac{\epsilon^5 |w_0|^2}{\tau_{\rm min}^4 M_p^2} \sim \boxed{\frac{\epsilon^5}{\tau_{\rm min}}} F^* F$$

Interesting axio-dilaton cosmology for DE and H tension

Conclusions

Conclusions

A cosmological constant is a great model for Dark Energy if you do not care about how it embeds into the rest of physics

Technical Naturalness provides a huge clue for Dark Energy because what is required by phenomenological success is difficult to obtain in the low-energy limit of known theories.

No known theory of Dark Energy yet threads the needle of Technical Naturalness, but if one does it seems likely to also involve light scalars and potentially interesting evolution.

Yoga Models use a combination of accidental scale invariances and supersymmetry of the gravity sector to provide a promising approach to Technically Natural Dark Energy, though its ultimate success is not yet clear


Fin

Extra Slides

Relevance to the Hubble Tension

Axiodilaton cosmology

5% increase in all masses at recombination helps with H0

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ (3)
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ (2)
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓ (3)
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ (1)
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ (1)
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ (2)
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ (2)
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ (2)
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	✗	-4.94	-0.94	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

H0 Olympics: 2107.10291

Axiodilaton cosmology

Need not be bad news (relevance to Hubble tension?)

5% increase in all masses at recombination helps with H0

Sekiguchi & Takahashi 2007.03381

CMB does not change (except small nonequilibrium effects) if:

$$\Delta_{m_e} = \Delta_{\omega_b} = \Delta_{\omega_c}$$

Changes H_0 because it changes epoch of recombination

$$\Delta_{a_*} = -\Delta_{m_e}$$

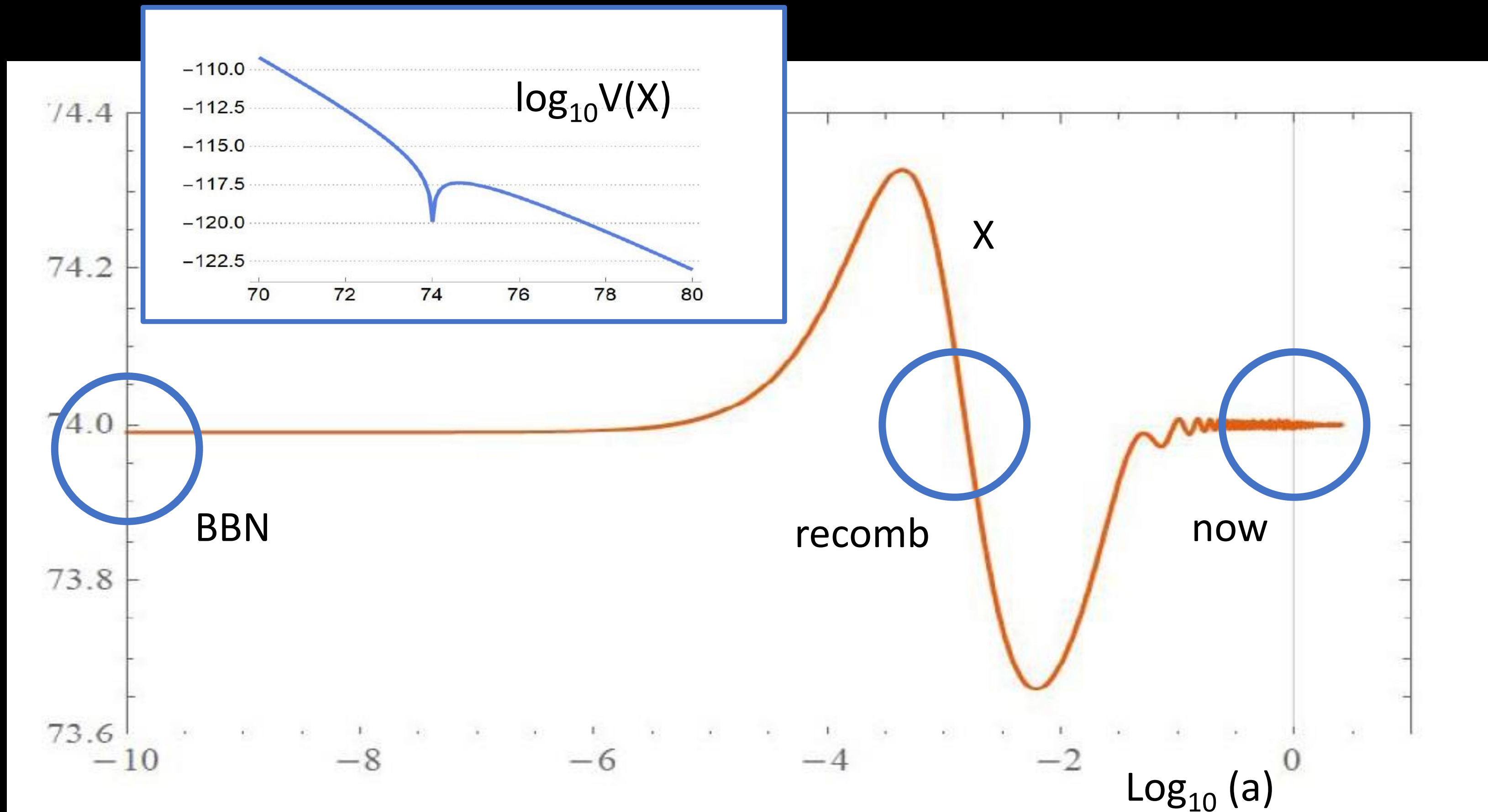
Leaves BAO unchanged if small spatial curvature

$$\Delta_h = 1.5\Delta_{m_e} \quad \omega_k = -0.125\Delta_{m_e}$$

Requires 10% reduction in τ ; equal abundance-shifts automatic

Axiodilaton cosmology

Dilaton evolution constrained because it changes particle masses relative to the Planck mass, leaving mass ratios unchanged



Relevance to inflation

Practical consequences for inflationary models

Two kinds of low-energy pseudo-Goldstone bosons with which to build technically natural inflationary string potentials, one class of which arises due to approximate scale invariances

Axions	Dilatons

Practical consequences for inflationary models

Axions Dilatons

Axionic inflationary models

- axions are ubiquitous
- axions have protected masses

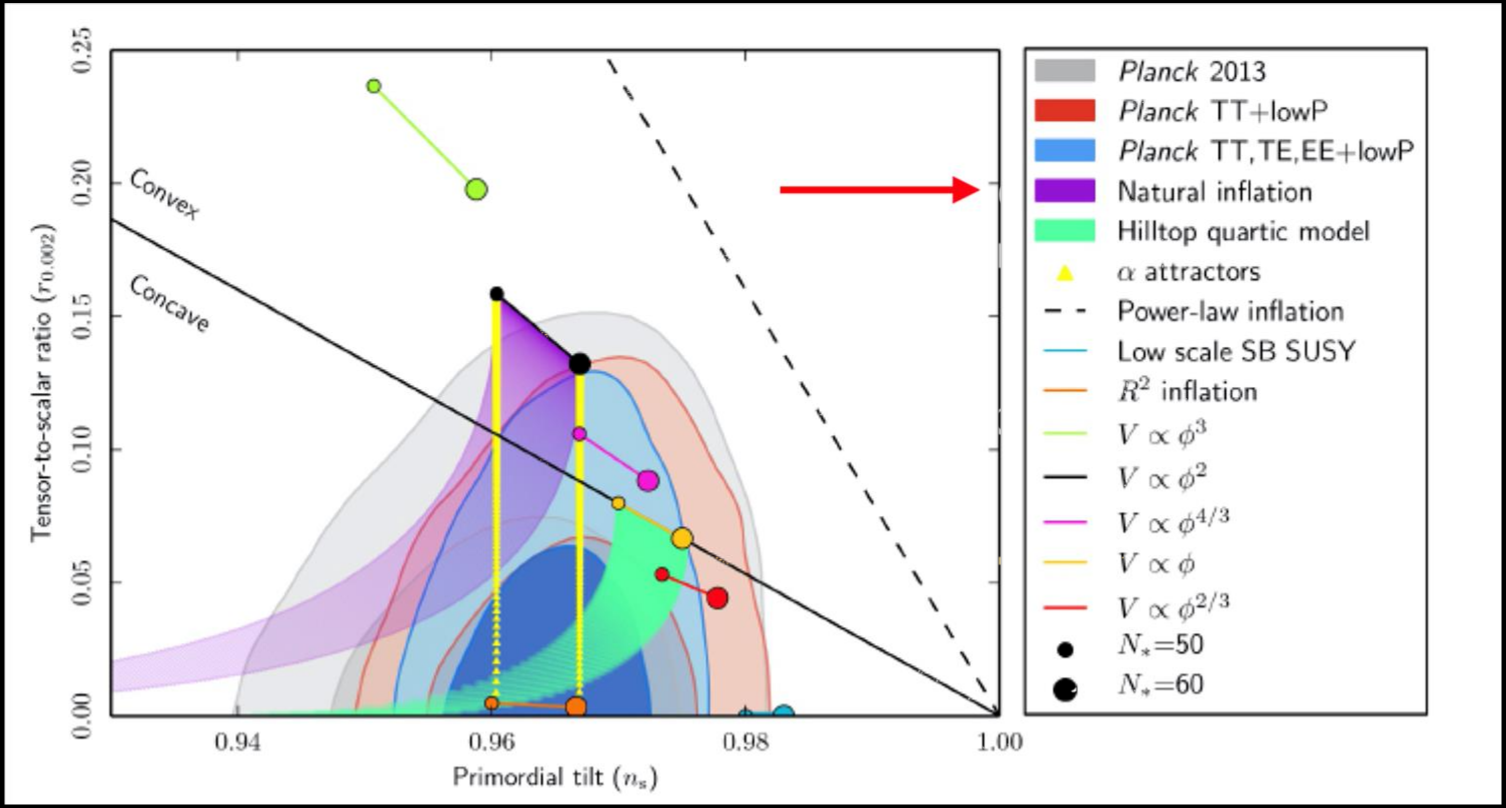
$$V(a) = A + B\cos\left(\frac{a}{f}\right)$$

Freese et.al. 90; Kachru et.al. 03;
Silverstein & Westphal 08 and more

Practical consequences for inflationary models

But: need $f \gg M_p$ disfavoured by data

Axions Dilatons



Planck collaboration

Practical consequences for inflationary models

Axions *Dilatons*

Scaling inflationary models

- Fibre moduli are ubiquitous
- F. mod have protected masses

$$V(a) = A - B\, e^{-a/f}$$

Goncharov & Linde 84; Kallosh & Linde 13 & 15

hep-th/0111025; 0808.0691; 1603.06789

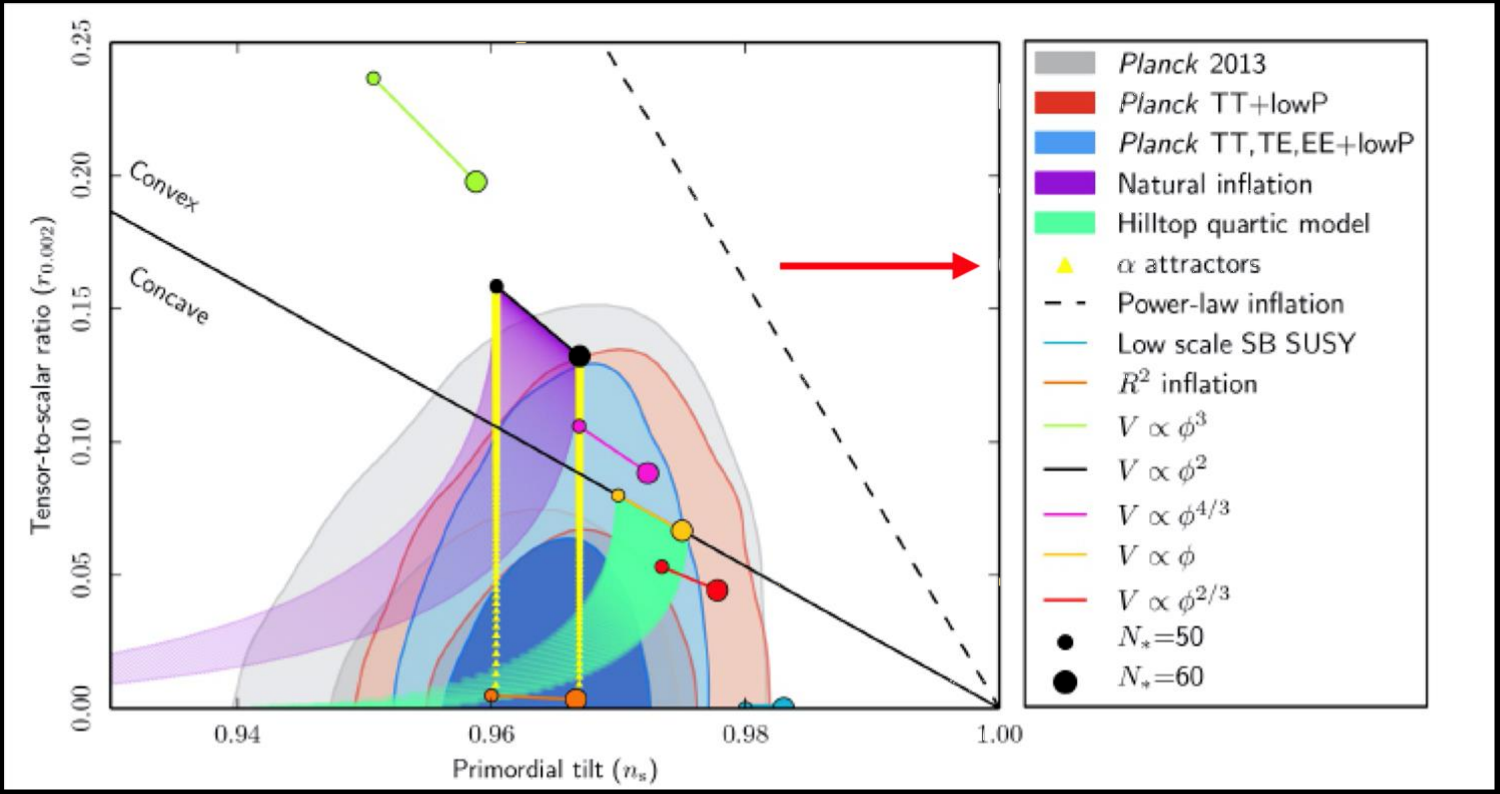
need $f \simeq M_p$

loved by data

predicts $r \simeq (n_s - 1)^2$

Practical consequences for inflationary models

Axions *Dilatons*



Planck collaboration

All This and More!

For microscopic inflationary models allows progress on the eta problem in ***two*** ways:

because of use of K for modulus stabilization

because flatness of potential is due to large field and not small parameter